COVER FEATURE

Cooled Filter/LNA Assembly Enhances Cellular Coverage

This cellular/PCS assembly provides performance levels close to HTS components even when operating at room temperature.

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CRYOGENIC technology has long promised near-ideal conditions for high-frequency designers-conductors with almost no resistance or insertion loss. The technology has already been applied successfully to cellular and personal-communications-services (PCS) base stations as part of filter/low-noise-amplifier (LNA) assemblies operating at cryogenic temperatures below 100 K. A practical evolution of this technology can be found in an innovative cross-coupled ceramic-filter/amplifier assembly from K&L Microwave Salisbury, MD) with 100-W power-handling capability and less than 0.5dB insertion loss at a center frequency of 1883 MHz. A six-stage design exhibits a 3-dB bandwidth of 4.5 MHz and a 40-dB bandwidth of 7.2 MHz. The noise figure (NF) of the integrated filter/LNA when cooled to 125 K is 0.71 dB.

High-temperature-superconducting (HTS) technology has found recent high-visibility applications in cellular and PCS base stations, in the form of assemblies using thin-film or coated thick-film HTS filters and cooled amplifiers. These assemblies feature low NFs that improve the sensitivity of a base station while increasing its operating range. Unfortunately, these assemblies require cryogenic cooling to approximately 77 K. A rise in temperature above the critical temperature (T_c) of the HTS components results in the loss of the superconducting state and a drastic increase in insertion loss.

As part of a program to explore practical applications for cryogenic technology, the engineers at K&L Microwave were able to develop a ceramic-filter-based assembly that does not suffer the extreme performance degradation of conventional HTS filters at temperatures above 100 K. The assembly leverages advances in ceramic materials to achieve resonant cavities with high quality factors (Qs) even at room temperature. Cooling to temperatures of 150 K or less only enhances the room-temperature performance of the assembly. The development program greatly benefited from design/financial assistance from the United States Naval Research Laboratories (see *Microwaves & RF*, February

1. The authors (Jeff Pond, kneeling, and standing, from left: Pradeep Halder, Rafi Hershtig, and Eric Moser) proudly display the cross-coupled ceramic filter.

1996, p. 38) and a proprietary cooling chamber developed by the Advanced Devices and Systems Group at Intermagnetics General Corp. (Latham, NY).

In most present architectures, a front-end filter/amplifier module is located in the base station, connected to the receive antenna by means of a long run of low-loss coaxial cable. Typical room-temperature filters are metal-cavity designs, with an insertion loss of approximately 1.5 dB By replacing these filters with the new cryogenic filter/amplifier assembly, system NF and sensitivity performance levels can be improved. By locating the assembly on the antenna, further performance improvement is possible.

The sensitivity of any base station can be improved by reducing the NF at the front end of the receiver, which translates to the ability to detect weaker signals. In any system, the background noise power (in W) is defined as kTB, where k is Boltzmann's constant, T is the operational temperature (in K), and B is the bandwidth (in Hz). A reduction of T or B leads to a reduction in the noise power. If the desired signal is passed with minimum loss, the NF is improved. Dropping the operational temperature to 77 K and below made it possible for conventional thin-film HTS filter assemblies to achieve low NF performance with improved receiver sensitivity in cellular and PCS base stations.

The NF of a component or system can be defined as:

$$NF\ (in\ dB) = 10\log F \qquad (1)$$

where:

F = (Si/Ni)/(So/No)

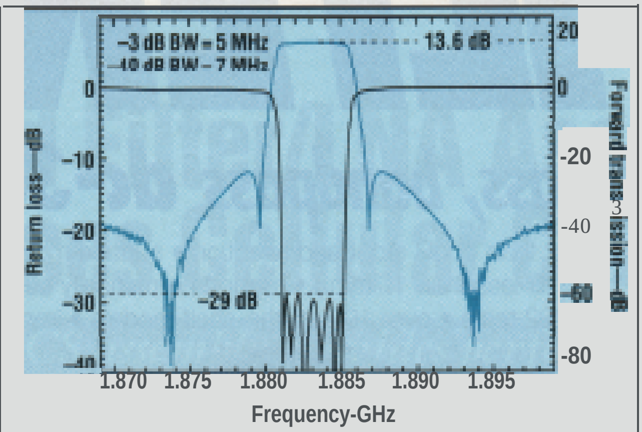
Here, Si/Ni and So/No represent the signal-to-noise ratio (SNR) at the input and output, respectively. For a passive component, in which there is no gain, the NF is defined as:

$$NF = 10\log Fi \qquad (2)$$

where:

$F1=1+(L-1)T/T0$,

L = the loss factor of the coaxial line,



2. The forward and reverse transmission characteristics of a six-pole elliptic-response ceramic filter with an integrated amplifier were measured at 135 K.

T0 = 290 K, and

T = the operational temperature.

By using a simple example, it is possible to demonstrate the improvement in NF from simply cooling a coaxial cable from 300 to 150 K. Assuming that a length of coaxial cable has 2-dB insertion loss (equivalent to about 70 ft. of cable), the loss factor is $L = 10^{(2/10)} = 1.58$. The NF at 300 K is therefore:

$$F_1 = 1 + (1.58 - 1)300/290 = 1.6 \quad NF\ (dB) = 10\log\ (1.6) = 2.04\ dB \qquad (3)$$

At 150 K, the NF due to the coaxial cable is a minimum of:

$$F_1 = 1 + (1.58 - 1)150/290 = 1.3 \quad NF_1 = 10\log\ (1.3) = 1.14\ dB \qquad (4)$$

This example demonstrates the correlation between NF and operational temperature. In reality, the advantage is even greater since the above argument ignores the reduction in insertion loss which occurs when a coaxial cable is cooled. The same analogy can be applied to a bandpass filter. The filter's bandwidth and insertion loss are two contributors to NF. For an ideal lossless bandpass filter, the noise power is kTB, with $K = 1.38 \times 10^{-34}$ J/K.

NF calculations on a cascaded chain of RF components readily show that when a filter/amplifier module can be placed at the top of an antenna (eliminating cable), the NF decreases. Given two RF components with a respective noise factor of F_1 and F_2,

Comparing cooled filters

Parameter	Cryogenic ceramic filter	HTS filter
Architecture	Ceramic-loaded waveguide in TE_{01} mode with nearly-ideal symmetric/asymmetric elliptic mode	Planar microstrip with skewed frequency response (difficult to tune/control)
Unloaded Q	23,000 at 300 K 30,000 at 150 K	25,000 at 60 K
Intermodulation	−160 dBm	Low IM performance
Third-order intercept	> +100 dBm	+70 to +80 dBm
Frequency stability	±2 PPM/°C	−1000 PPM/°C at 77 K −100 PPM/°C at 60 K
Power handling	> 100 W for multisection design	50 W maximum
Size of filter	100 in.^{3}	10 in.^{3}
Applications	Transmit/receive	Receive only
Filter temperature	Maintains response from operational temperature to room temperature	Performance degrades dramatically above the critical temperature
Cost of cooler	Low	High
MTBF of cooler	> 100,000 hr. at 150 K	8000 hr. at 77 K

the cascaded NF (NF_{cas}) of the combined components is:

$$F_{cas} = F_1 + (F_2 - 1)/G_1 \quad (5)$$

where:

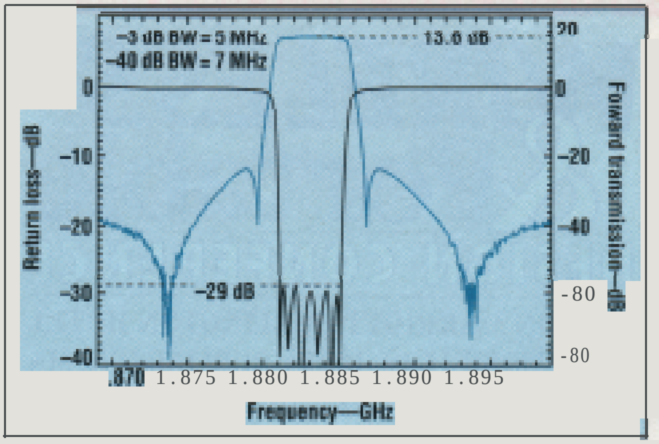
G_1 = the gain of first component, then NF_{cas} (dB) = 10 log (F_{cas}).

The new filter/amplifier assembly (Fig. 1) is based on three guidelines:

- Maximizing the unloaded Q of the filter resonator at room temperature.
- Attaining a cooled temperature with reliable cryogenic refrigerators (between 125 and 170 K).
- Optionally placing the filter/amplifier at the top of the antenna.

Availability of high-quality ceramic resonators supports the design of wireless communications filters with high stability and reliability. These new ceramic resonators are capable of a temperature stability of approximately ±2 PPM. This implies that in terms of frequency drift, the filter performance remains nearly constant, between room temperature and the lower operational temperature (125 K). In the rare event of a cooling failure, a small degradation in NF (approximately 1 dB) occurs. Still, this slight performance degradation does not disrupt the RF link. Since these resonator-based filters continue to provide high performance at room temperature (see table), there is no need for the bypass switches and failure-detection circuitry common to HTS filters.

With the new ceramic materials, the unloaded Q for a resonator with a 2.4-in. (6.096-cm) diameter is typically 25,000 at room temperature (300 K). When incorporated in a quasi-elliptic design, these resonators yield a filter with very-low loss and sharp rolloff. This response is ideal for rejecting co-channel interference in cellular and PCS systems. When cooled to 125 K, the loaded Q improves a minimum of 20 percent. The unloaded Q can be further improved by 10 to 15 percent with several methods, including the use of ceramic tuning disks instead of metal screws, or low-loss ceramic standoffs. The increase in Q further reduces the insertion loss of the filter in front of the low-noise amplifier (LNA), resulting in an overall reduction in front-end NF.

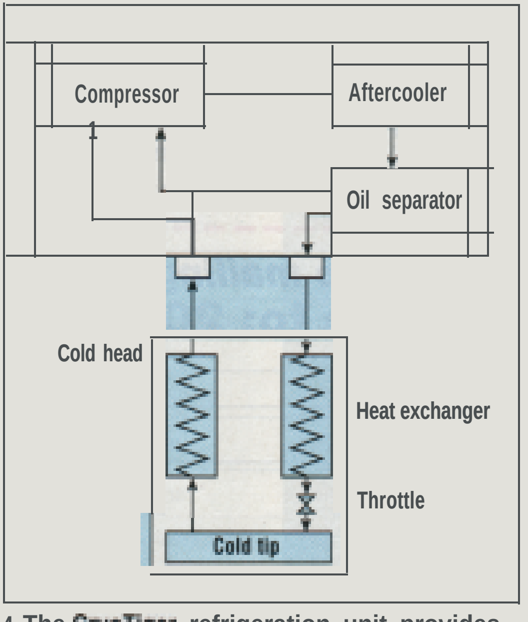


3. The 1-dB compression and third-order-intercept performance of a six-pole elliptic-response ceramic filter with an integrated amplifier were measured at 135 K.

The new ceramic filter achieves power-handling capability of approximately 100 W. Although this filter/amplifier assembly is designed for receive applications, it may also be required to sustain moderate power levels in some antenna configurations. For transmit filters that require low insertion loss and high power-handling capabilities, the same approach can be applied.

The robust design of the new filter permits tuning at 125 K. Use of a special test fixture developed at NRL aids in matching the filter to the limited input VSWR of the LNA. Since the design of the amplifier represents a trade-off between gain, NF, bandwidth and third-order intercept point (IP3), fine tuning at the operational temperature is essential for optimum performance. In the tuning process, the resonant frequency, the mutual coupling values, and the external Q are adjustable. With this flexibility, the transmission zeros can be placed upon request, depending on local interference.

Design of the cross-coupled ceramic base-station filter called for the realization of four finite transmission zeros (two on each side of the passband) and eight infinite zeros (one at DC and seven at infinity). In total, the number of resonators is (4 + 1 + 7)/2 = 6. The filter design is based on a canonical structure of N = 6. In the main path, resonators 1,2,3 and 4,5,6 are magnetically coupled. Resonators 3,4 and 1,6 are electrically coupled producing two quadruplets of resonators (2-3-4-5 and 1-3-4-6) that realize two transmission zeros on each side having two equal-minimal points.



4. The CryoTiger refrigeration unit provides reliability, efficiency, and compactness, without adding overbearing cost.

With the help of computer-aided-engineering (CAE) tools, the filter network was synthesized and the coupling values were calculated. Even though the aim of the design was to maximize the unloaded Q, the filter was not fully optimized. For instance, its metallic tuning disk could have been replaced with a ceramic tuning disk for higher-Q performance. Furthermore, resonators were supported by Lexan rods. Replacing these with low-loss alumina standoffs could also increase the Q. These changes could improve the loaded Q by 5 to 15 percent. The inherent +2-PPM frequency drift of the resonators is easily compensated with tuning disks. With cooling, the filter's insertion loss of

0.8 dB at 300 K drops to 0.5 dB at 125 K. For improved stability, it is possible to specify the ceramic resonators with some negative temperature coefficient (such as -2 PPM) for a balanced set of resonators that has negligible frequency drift as a function of temperature.

Once the filter was developed, a commercial LNA was cascaded with the filter and physically attached to the filter's housing for thermal considerations. A tuning fixture was built to facilitate integration of the two components at 125 K. By fine tuning the last stages of the filter, input return loss (as seen by the antenna) of 25 dB was achieved (Fig. 2). Measurements of the 1-dB compression point and IP3 were conducted at 135 K (Fig. 3).

The cryogenic cooler and packaging are important components of the filter/amplifier assembly. A cost-effective approach is to use standard refrigeration technology that has been extended to cryogenic temperatures to achieve operational temperatures of 150 K and less. The CryoTiger® refrigeration unit from Intermagnetics' subsidiary, APD Cryogenics, provides good reliability, efficiency, and compactness, without adding overbearing cost. Unlike Gifford-McMahon and Stirling cycle coolers, the cold end does not contain any moving parts and has a high mean time between failures (MTBF) of more than 100,000 hours. The CryoTiger throttle-cycle refrigerator is based on Joule-Thomson expansion of a gas through a throttling valve into an expanded space. The expansion valve and counterflow heat exchanger do not contain any moving parts, and a reliable, oil-lubricated compressor does all of the work required for the refrigeration system (Fig. 4). The compressor runs on a standard 115 VAC and uses less than 500-W input power.

A variety of different gas mixtures can be used with the CryoTiger, providing a selection of different characteristic curves. The 120-to-150-K temperature range is moderate since it can be easily reached by the cooling system and substantial benefits can be gained in microwave performance.

Several packaging techniques are used to enable cooling of the filter and LNA to cryogenic temperatures. The key is to thermally isolate the cryogenic components well enough to allow the refrigeration system to cool them down with tolerable heat-leak (wattage) levels. The equation for calculating thermal budget is:

$$Q = kA\frac{\Delta T}{\Delta x}\Bigg| \quad (6)$$

where the cooling (or heating) power Q (in W) required depends on the thermal conductivity k of the medium (in W/cm/K), the temperature difference DT (in Kelvin), and the length Dx and area A of the conduction path. (Multiple heat-conduction paths are summed.) The thermal conductivity is also generally dependent upon temperature. The thermal resistance is analogous to electrical resistance, with temperature drops analogous to voltage drops, and wattage analogous to electrical current.

High-frequency interconnections to the filter and LNA are an important part of the total design. Ideally, these connections should feature low microwave loss but also low thermal conductivity, two traits not commonly found together. A trade-off is reached by using stainless-steel coaxial cables, with somewhat higher microwave losses than copper but with better thermal properties than copper cables. The filter and LNA are securely linked to the cold head for low thermal resistance.

How does the cooled filter/amplifier assembly impact overall cellular or PCS base-station performance? Most cellular or PCS service providers are concerned with optimum coverage. As the NF of a base transceiver station (BTS) decreases, its sensitivity and effective range increases. The enhanced range of a single BTS translates into fewer base stations per given area.

However, the improved NF performance may not support increased capacity. When the concern shifts from the coverage of a large area to capacity, the need changes from improved NF to filters with sharp roll-off that can reduce co-channel interference. Under this circumstance, an improved NF does not have a direct impact on a BTS's capacity. Due to the deployment of the cellular underlayer, the SNR increases anyway. These two extremes-coverage of a large area with low background noise and the need for increased capacity in high-density population areas-imply the existence of many intermediate situations requiring case-by-case optimization of system performance. As a result, the NF must be improved by finite levels for different performance scenarios.

This is possible when several options of RF connections and cooling are tested. At the antenna level, new designs enable increased gain while optimizing the directivity pattern. In addition, antennas with built-in LNAs can improve the NF by avoiding cable interconnections. Exploiting coaxial cable with larger cross-sections can reduce the RF insertion loss in front of the LNA.

Several options of architectures are suitable for tower-mounted antennas (TMAs) and the associated NF improvements when compared with conventional approaches. The possible trade-off among the architectures can impact cost dramatically. For instance, cooling the cross-coupled ceramic filter to 125 K improves the NF by approximately 0.4 dB. Since this module does not depend on HTS material properties, in cases where this improvement can be tolerated, another attractive option is cooling the LNA only.

The cryogenic ceramic-filter/amplifier assembly can be specified for cellular and PCS frequencies, at customer-specified center frequencies and bandwidths. The assemblies can be provided with or without CryoTiger refrigeration units for ease of installation into communications systems. In addition, the low-loss, low-NF filter technology can also be applied to other commercial and military applications areas, such as radar systems, surveillance and intelligence-gathering receivers, as well as electronic-warfare (EW) systems. **K&L Microwave, Inc., 408 Coles Circle, Salisbury, MD 21804; (410) 749-2424, FAX: (410) 749-5725, Internet: http://www.kl-microwave.com, e-mail: klsales @klmicrowave.com.**

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